DUAL SWITCHING OF BLUMLEIN GENERATORS

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ABSTRACT

We have developed a series of techniques which are useful for operating two Blumlein generators from one Pulse power source, or a single Blumlein with two separate lines and switches. These techniques and operating experience with these devices are outlined in this paper as applied to the Gemini dual Blumlein, and the Tempo device with two switches.

INTRODUCTION

In many applications there is a requirement to fire two high power pulse generators at a controllable relative time interval. These applications include Z-pinch experiments[1], High Power Microwave experiments[2], Particle Beam Fusion[3], Collective Ion Acceleration[4] and Radiation Effects studies[5]. If many high power generators are required, they must in general be separate units, however if 2-4 units are required simpler hybrid pulse power sources may be a viable option. In this work, we present the results of an experimental program in which we developed pulse power techniques which facilitate the operation of 2 (or more) pulse power output pulses at the same time.

We discuss two examples of dual Blumlein devices, the Gemini device and the Tempo device. The latter device uses a single Blumlein with two parallel sections which are fired by two triggered switches, leading to an improved pulse shape. The output of the line is recombined at the load end. The triggering technique is the same as that used in the Gemini Blumlein.

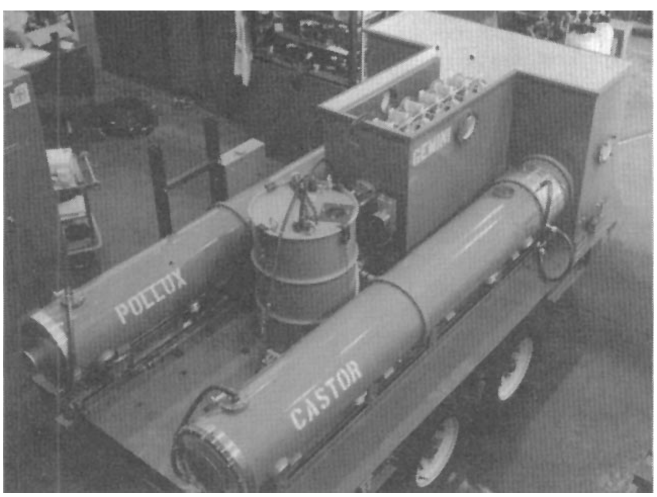

Fig. 1 - Gemini Device

DESIGN AND OPERATION OF THE GEMINI DEVICE

The GEMINI device, shown in Fig. 1, makes use of novel induction techniques to allow two Blumlein pulse forming networks to be charged by the same Marx generator and discharged at different times. The timing circuits are unique in that they make use of saturable magnetic circuits to provide the relative timing of the two outputs. This technique is both more controllable than other techniques and more reliable. In fact, the relative timing set by the operator has never failed as a means of controlling the relative timing of the switch firing. In this paper, we outline the issues involved in the pulse power design (section 2), the solutions (section 3), the performance of the GEMINI device (section 4), and the application of similar techniques to the Tempo device (section 5).

PULSE POWER ISSUES

Isolation of Two Blumleins

The pulse from a Blumlein circuit is initiated when the intermediate conductor, which is connected to the Marx generator, is closed to ground. This practically amounts to shorting the output of the Marx generator to ground, as is clear from the diagram of Fig. 2a. If we attempt to operate two Blumleins from the same Marx generator without some form of isolation between the two, closing the switch on one Blumlein will initiate a pulse on the second one, and operation of the two devices at two different times will be impossible. If we attempt to put isolation in the charge lines between one of the Blumleins (or both Blumleins) and the Marx, then we must either reduce the energy transferred (resistive isolation) or increase the charge time (inductive isolation). Neither approach is desirable-we wish to have the highest possible energy output from the Marx, and if the charge time is increased, the high voltage insulation properties of the water in the Blumlein are degraded.[6]

Timing Circuits

In high voltage pulse power environments, there are many noise sources which radiate electromagnetic radiation powerful enough to cause TTL level inputs at timing generators, etc. Without extreme care in the positioning and shielding of cables, spurious signals associated with the firing of Blumlein number 1 will trigger Blumlein number 2. A reliable triggering system based on fundamental physical principles is therefore desirable.

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PULSER DESIGN

The name chosen for the two pulse accelerator was Gemini, with two arms Castor and Pollux. Each stage in the Marx consists of a Maxwell type 77073-1 midplane spark gap and a pair of low inductance .33 microfarad capacitors. Resistive biasing of the midplanes was utilized and our design goal was 80 kV typical, and a stored energy of 10 kJ.

A schematic of the Blumlein circuit, switch and switch trigger circuit is shown in Fig. 2a for fast risetime single line operation and in Fig. 2b for variable delay two-line operation.

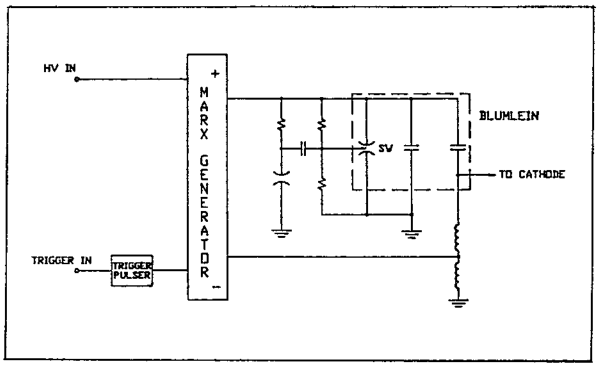

Fig. 2a - Schematic With Single Blumlein

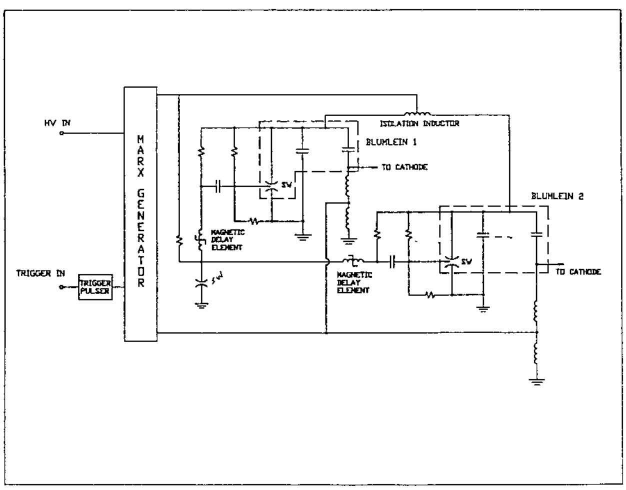

Fig. 2b - Double Blumlein Schematic With Magnetic Delay

This figure shows the essential unique features of the design solutions to the problems set forth in Section 2.0. The solution to the Blumlein isolation problem is a bucking isolation inductor, which has low inductance during Blumlein charge and high inductance when one Blumlein switch is closed. The solution to the inter-arm timing problem is a magnetic-based high voltage trigger delay unit. Once the master trigger unit fires, the preset magnetization of the magnetic cores delays the trigger pulse to the Blumlein. A switch was fabricated with a larger conduction diameter in order to increase the gas volume and facilitate the formation of a larger number of arc channels in order to overcome some of the drawbacks of the Rapier switch. These innovations are described in turn below.

Isolation Inductor

The isolation inductor is fabricated from two parallel 3/8" lengths of copper tubing wound in a solenoidal configuration on a 6 inch diameter mandrel 21 inches long with a total of 7 1/2 turns in each coil. The wire ends are connected so that the currents from the parallel wires are opposite when the Marx is charging the two Blumleins. The flux in the solenoid will be close to zero as long as the two currents are equal. When Blumlein switch A closes, Blumlein B would normally discharge. In order for it to discharge, however, the direction of current flow in the A leg must reverse, and the fluxes from each coil half will then add in the solenoid. If we switch A before the lines are fully charged, current will still be flowing in the inductors, and for some parameters, B may still continue to charge.

The ratio of the inductance for counter-flowing currents to the inductance for co-flowing currents is of interest as a measure of the degree of isolation available. In a practical design we wish to have the counter-inductance much less than the Marx plus Blumlein inductance, and to have the co-inductance much greater than the output pulse length squared divided by the Blumlein capacitance. This latter condition is equivalent to an energy drain much less than the stored energy. The former condition is equivalent to having the counter inductance less than twice the Blumlein charging time squared divided by the Blumlein capacitance where we have assumed that the Marx capacitance is equal to the sum of the Blumlein capacitances. If we assign the inequality very much greater than a value of 20, we find that we must have:

$$\frac{L_{co\text{-}flowing}}{L_{counter\text{-}flowing}} > 400\left\{\frac{\tau_{discharge}}{\tau_{charge}}\right\}^2$$

For the original Rapier accelerator, the charge/discharge time ratio was approximately 6, and so we required a ratio of inductances of approximately 10.

The co-inductance may be found from the simple solenoidal inductor formula, and the counter-inductance is proportional to the length of the wire when we assume a wire diameter to inter-wire spacing ratio of 3. After appropriate manipulation, we find that the ratio of co to counter inductance is given by 7.6nr where n is the number of turns per unit length, and r is the coil form radius. This condition is in practice easy to satisfy. In the Gemini design, values of 32 turns per meter and r=9 cm. were used. A measurement of the inductances gave us the required values of 22 microhenries in the co-flowing case, as compared to 2 microhenries in the counter-flowing case.

Magnetic Timing

In a conventional magnetic switch, the magnetic core is magnetized before the shot to achieve the maximum value of internal magnetic field, which is in turn proportional to the volt-second product applied before the core material saturates. Once that volt-second product has been applied to the core, the core

winding inductance drops, and the switch transitions from open to closed. The switch becomes a timing element when we set the magnetic field, and therefore the volt-second product, to a lower value. Barring a failure in the switch itself, a prefire is not possible if the switch is set properly.

In the magnetic timing circuit which we utilized, a spark gap which breaks down at a preset voltage level applies voltage to two magnetic switches--one in each Blumlein switch trigger line. When these switches saturate, they apply a trigger pulse to the Blumlein switch, and the Blumlein pulse is subsequently initiated. The requirements on the magnetic timing elements are that they have the required volt-second product while having low enough inductance to give rise to a fast-rising pulse at the switch trigger blade.

The trigger system is set up to produce a pulse with a voltage of 2/3 the Marx voltage or a maximum of 320 kV. The required interpulse spacing was 200 ns. so the required volt-second-turn product was V =.064 volt-seconds. The capacitance of the trigger is approximately .4 nf. and we wish to have a quarter-cycle trigger risetime of 40 ns. This gives rise to a maximum allowable inductance of 4 H. The switch, due to its high voltage, must be insulated from ground, requiring a minimum spacing of approximately 2 cm. from the wall. This distance defines an effective minimum to the inner diameter of the inductor conductor chosen to be approximately .8 cm. for our geometry. With a core radial thickness r of .7 cm. we find the inductance per unit length to be .6 microhenries per meter. The maximum allowable length is then 6 meters. The material chosen for this application is 2 mil thick tape wound silicon iron with a flux swing of B=3 Tesla. The minimum length is determined from the relationship Bl r=V =.064, and so we find 1=3 m. for each magnetic timing unit.

Switch Design

The Blumlein switch was designed with the objectives of long life and low inductance. The switch inductance depends on the number of current carrying channels which are formed when the switch is triggered. We chose the design shown in cross-section in Fig. 3.

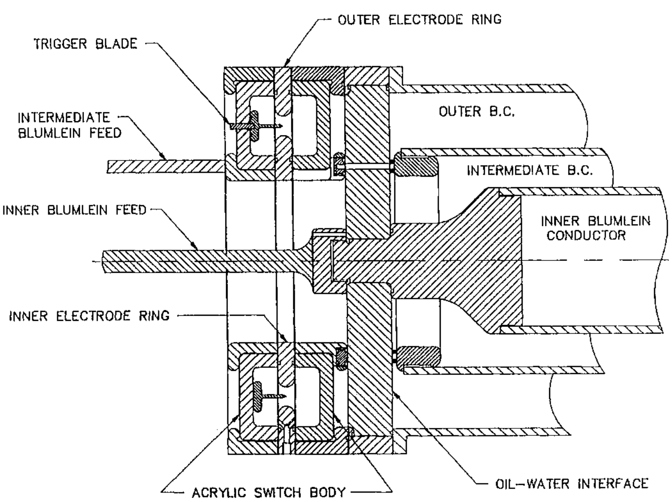

Fig. 3 - Section Showing Railgap Switch

This design results in a current path which is an excellent approximation of the ideal radial termination of the coaxial line. By building a sufficiently large switch, we insure that the shock due to closure of a single arc channel, with commensurately large energy deposited in the arc, will not result in failure of the switch. The use of a large diameter for the electrodes reduces the damage per unit length of electrode, and therefore increases life. Consistent multichannel operation also increases life since the damage in an individual arc spot is proportional to some constant times the current plus some constant times the current squared. Single channel switching rapidly damages the electrodes, whereas multichannel operation will result in only minor damage.

Pulse Power Performance

The Gemini device has performed at or beyond design specifications in all aspects of its operation. Data are presented here on Blumlein isolation, operation of the magnetic delay circuit, Blumlein switch channel multiplicity and distribution, and pulse risetime. A total of over 1000 pulses have been taken with the device with no significant failures and 2 Hz. operation of the device is now contemplated.

Switch Performance

The multichannel performance of the Blumlein switches was studied by the use of an aqueous copper sulphate load resistor. The outer insulating surface contained optics enabling a camera to view the railgap by looking down the length of the water in the line.

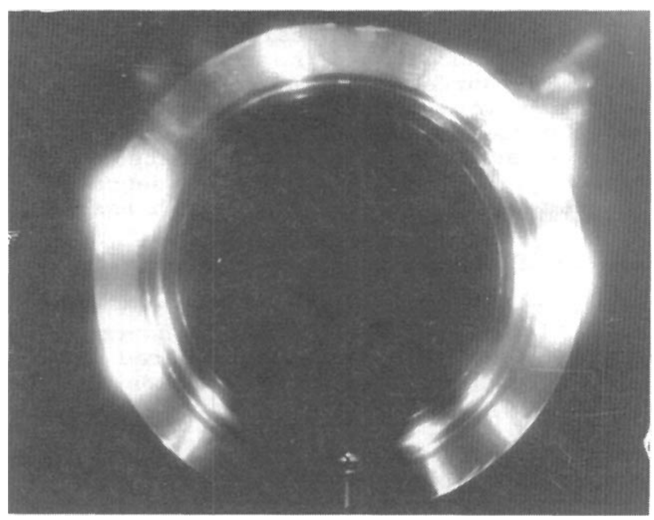

Fig. 4 - Photograph Of Blumlein Railgap Switch

As can be seen in Fig. 4 a detailed view was obtained of the radial distribution and intensity of the arc channels. The number of switch channels as observed optically increases approximately linearly with charging voltage. This can also be inferred from the observation that risetime decreases with increasing charging voltage. We expect this because the trigger voltage is not fixed--it increases with increasing Marx voltage.

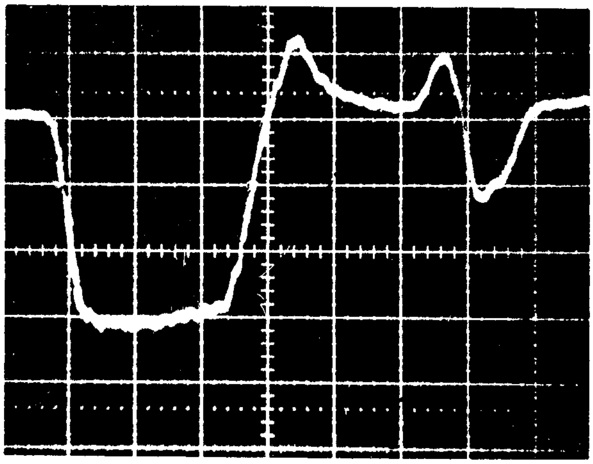

Fig. 5 - Fast-rise Blumlein Pulse

Fig. 5 shows an output voltage waveform from the test switch with a fast trigger pulse, giving a risetime of about 20 nS. About thirty shots were also fired at 30 KV charging voltage with no trigger to the railgap mid-plane. These shots all created only a single channel in the switch. Single channel switch operation, even at the highest voltages, did not lead to switch damage or failure.

When the test switch was examined after approximately 900 shots it was determined by counting arc impact points that the average number of channels per shot was 3.7 averaged over all voltages.

The circumferential distribution of channels was also determined from the switch photographs, and found to be random.

With an aggregate of more than 10,000 shots on three switches of this design, only moderate wear was observed and no damage could be found. The surface roughness due to arcs was discernable to the touch but was easily removable with light sanding with emery paper. Electrode surfaces were bead-blasted before reassembly. No other damage or degradation was noted in any part of the switch assembly.

<u>Dual Blumlein Operation</u>

After proper operation was obtained with a single Blumlein the separation inductor was installed and both lines were fired from a single triggering source. Operation in this mode was as predicted. The timing jitter was less than 10 nS at 80 kV, and pulse height symmetry was within 5%. A typical dual Blumlein shot is shown in Fig. 6.

No major problems were encountered in converting the machine from single to double Blumlein operation.

The first task in characterizing dual Blumlein operation was to measure the interpulse time delay as a function delay setting and Marx generator charge voltage. Time delay was measured at 40, 60 and 80 KV. Delay was proportional to the magnetic core preset voltage over the complete range as shown in Fig. 7.

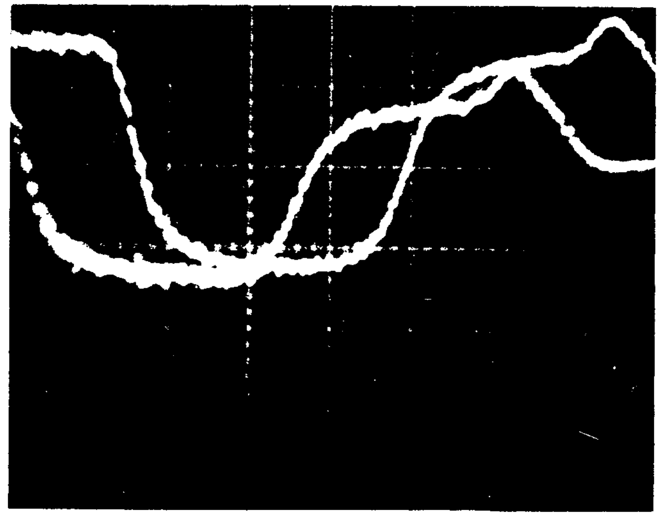

Fig. 6 - Dual Blumlein Shot With 75nS Separation

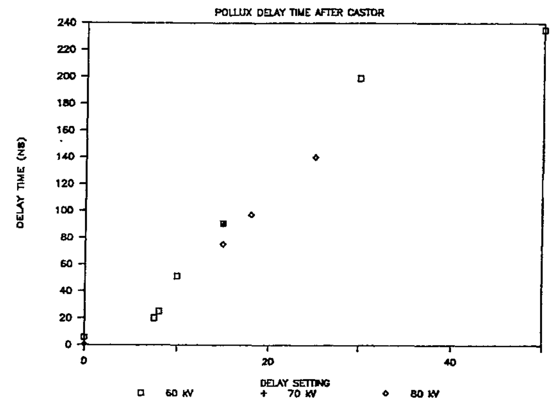

Fig. 7 - Magnetic Delay Calibration

At the longest delay settings the precursor voltage is observed to be less than 8% of the peak voltage. The precursor voltage results from current which flows through the isolation inductor.

TEMPO

Tempo[7] is a single Blumlein, however is fired by two switches, and the output of the line is recombined at the end of the line as can be seen in Fig. 8.

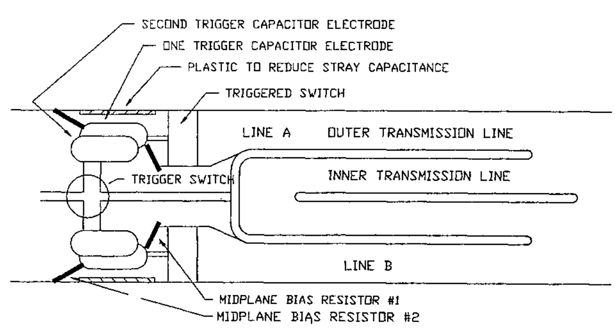

Fig. 8 - Plan View Of Tempo Device

The triggering technique is the same as that used in the Gemini Blumlein, with the magnetic switches replaced by a spark gap, however the use of two triggered switches leads to an improved pulse shape.

The parallel switch concept was originally proposed by G.Rohwien of Sandia National Laboratories as a technique for reducing the risetime of a planar Blumlein. This is required because the switch end of a planar Blumlein is intrinsically more inductive than the switch end of a cylindrical Blumlein. The physical layout of the Tempo machine is shown in Fig. 8, along with the physical layout of the trigger components. The critical issue was to produce a trigger pulse for the midplane switches which had a sufficiently fast rise in order to trigger both switches. In order to accomplish this, the coupling capacitors were made from two cylinders with rounded ends. Since water was the ambient medium, the capacitance between these two cylinders is large enough to provide the requisite pulses.

We initially connected the self-break trigger switch between the resistor and ground. Successful triggering of both switches was only observed in this mode on 1 out of 5 shots. We then reversed the polarity of the resistor and switch. The reliability of two-switch triggering was then observed to be approximately 95%. We speculate that the reason for this was based on the polarity of field enhancement in the midplane switch. The Tempo intermediate conductor was charged in the positive polarity. The electric field which initiates the switch triggering process causes the electric field between the grounded switch electrode and midplane to increase by a factor of 3, which in turn causes it to break down. The field in the other half of the switch is then enhanced by a factor of 2. In the favored polarity, the field enhanced midplane electrode is negative, after the first half of the switch breaks down. The field enhancement of the midplane electrode gives rise to electron injection at this electrode which speeds breakdown. In the opposite polarity, the midplane is positive, and no electrons are emitted into the gas from either electrode. This interpretation was supported by voltage waveforms which were consistent with breakdown of only half the switch. In these waveforms, voltage was observed on the Blumlein output, but the discharge of the line occurred on an extremely slow time scale, consistent with discharge of the line through the resistors.

Waveforms which illustrate the output current pulse (into a resistive load) are shown in Fig. 9a and 9b.

Waveforms for single switch and double switch firing are shown. The shape of the pulse is clearly superior if two switches fire. The precursor in the 2-switch firing case is due to coupling between the trigger and the main line.

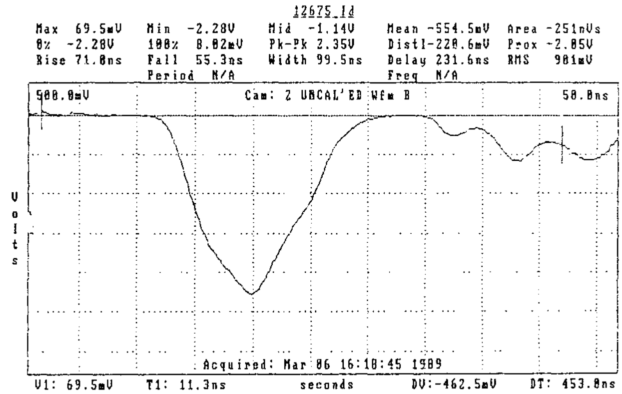

Fig. 9a - Single-Switch Tempo Output Pulse

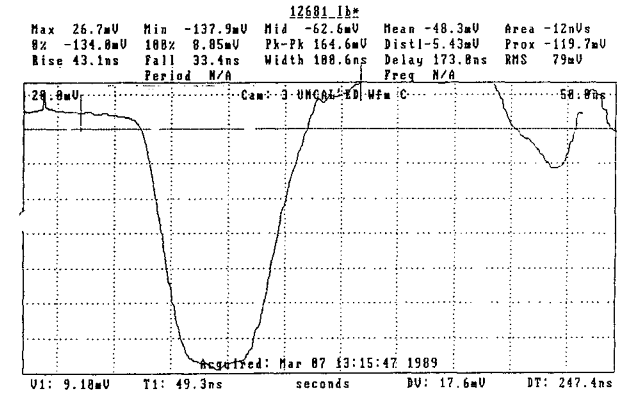

Fig. 9b - Dual-Switch Tempo Output Pulse

CONCLUSION

We conclude by noting that firing of parallel switches in a single Blumlein, or firing of parallel Blumleins can be accomplished by using a self-breaking switch in order to trigger midplane spark gaps. These techniques have been demonstrated on two pulse power machines.

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